Massive Damage Assessment Program and Repair and Reconstruction Strategy in the Aftermath of the 2010 Haiti Earthquake

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The January 2010 Haiti earthquake resulted in over 230,000 deaths, affected 3 million people, and damaged or collapsed over 200,000 structures. An unprecedented earthquake damage assessment project by a joint operation of the Haitian Ministry of Public Works, the United Nations Office of Project Services, the Pan American Development Foundation, and the authors was undertaken with three strategic goals: (1) rapid damage assessment, (2) reconstruction database development, and (3) upgrade the technical capabilities of Haitian engineers. A modified version of the Applied Technology Council's *ATC-20* technical platform, accounting for Haitian building design, was developed. As part of this program, PDA-based data collection techniques and quality-assurance programs were implemented, and approximately 600 Haitian engineers were trained. As of March 2011, approximately 400,000 buildings had been inspected. This database was used to develop: (1) repair strategies for yellow-tagged structures, and (2) reparability, reconstruction, and demolition assessments or red-tagged structures. This program could also be extended as a platform for a seismic damage evaluation and reconstruction strategies in other parts of the world. [DOI: 10.1193/1.3631293]

INTRODUCTION

The catastrophic 2010 Haiti earthquake has had a tragic effect on the lives of more than 3 million people. This paper describes the work performed by the Haitian Ministry of Public Works, Transport, and Communications (MTPTC) to rapidly assess the safety and reparability of much of the affected building inventory in Port-au-Prince and other affected communities. It also describes probability damage functions developed from the assessment database. This paper addresses key strategies concerning the repair of damaged structures and the removal of collapsed and irreparable buildings.

In light of the enormity of the damage caused by the earthquake, the MTPTC created the Bureau d'Évaluation Technique des Bâtiments (BETB), a dedicated agency charged with the task of assessing damage to all buildings in earthquake-affected areas, developing criteria for repair and reconstruction, and providing reconstruction quality control (QC). With funding provided by the World Bank (WB) and the U.S. Agency for International Development (USAID), field logistics provided by the United Nations Office of Project

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Services (UNOPS) and the Pan American Development Foundation (PADF), and technical expertise provided by the authors, BETB embarked on an ambitious program to organize and train a cadre of approximately 600 Haitian national engineers to perform a rapid damage assessment of all affected buildings using the Applied Technology Council's *ATC-20* (ATC 1987) and the Federal Emergency Management Agency's *FEMA 310* (FEMA 1998) methodologies.

The authors led a four-day intensive classroom session on the fundamentals of earthquake engineering and training for more than 600 applicants. Coursework was followed by a written examination, from which approximately 250 candidates were selected as the initial teams of evaluators. Among these, ten of the most qualified were selected as division leaders. Division leaders were given additional field training prior to commencing work with their division engineers. Each of the divisions consisted of a division leader, four team leaders, and eight to ten evaluators, all taken from the ranks of the 250 trainees.

2010 HAITI EARTHQUAKE

OVERVIEW

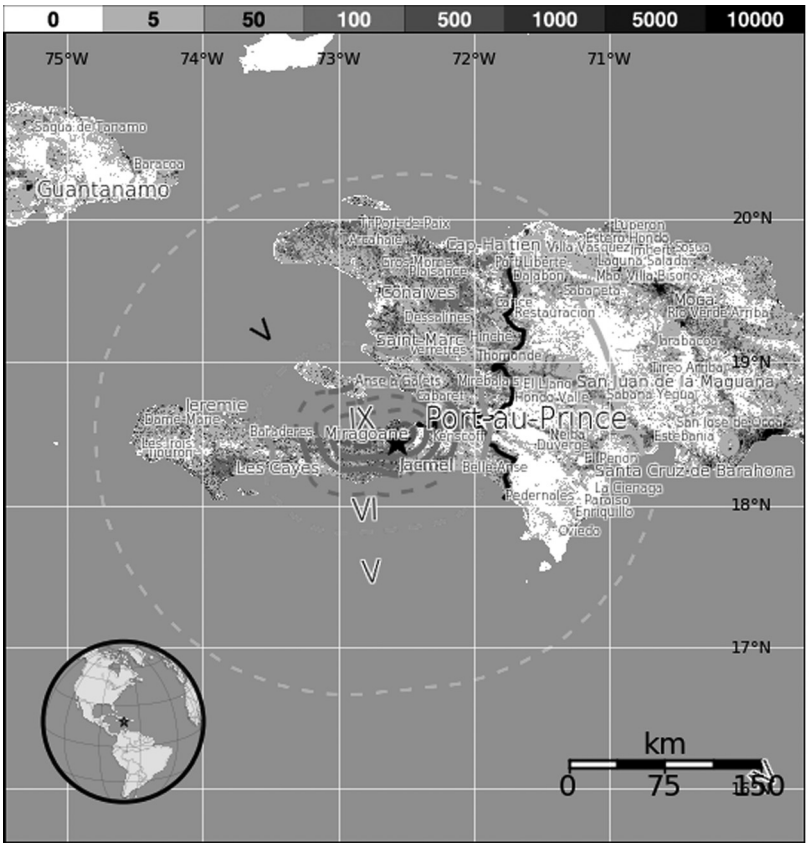
The magnitude 7.0 Haiti earthquake occurred at 16:53 local time on Tuesday, 12 January 2010, with an epicenter approximately 25 km west-southwest of the densely populated capital city of Port-au-Prince. The main event induced shaking based on modified Mercalli intensity (MMI) VIII in the city; see Figure 1 (USGS 2011). In the two weeks following the main event, at least 52 aftershocks in the magnitude range of 4.2 to 5.9 were recorded.

Haiti has experienced previous large (but infrequent) earthquakes. The last major earthquake to strike Port-au-Prince was the 1770 event that leveled the city. In 1842, an earthquake destroyed the city of Cap-Haïtien in northern Haiti. Another large earthquake occurred in 1860 which resulted in a tsunami. It should be noted that the last major earthquake to occur in Haiti dates back over 150 years. This lack of significant seismic activity for a long duration prior to the 2010 event resulted in the following consequences:

- Reduced importance and priority assigned to the proper seismic design, proper detailing, and construction by both the public and private sectors.
- A large pool of vulnerable structures was preserved. In areas of the world that experience more frequent seismic events (such as California), each earthquake eliminates a number of weak structures through collapse. Therefore, fewer vulnerable buildings remain and are subject to subsequent earthquakes. This was not the case in Haiti.

The 2010 earthquake caused significant damage to Port-au-Prince and other cities in the region. More than 200,000 structures were damaged or had collapsed, including many essential buildings, such as the Presidential Palace (see Figure 2), the National Assembly building, Port-au-Prince Cathedral (see background of Figure 4), and Port-au-Prince's main jail. The headquarters of the United Nations Stabilization Mission in Haiti (MINUSTAH) also collapsed (see Figure 3), killing many, including the mission's chief.

The Haitian government reported that more than 230,000 people died, 300,000 were injured, and 1.3 million were made homeless (MTPTC 2010). Six months after the earthquake,



Est. MMI	Est. Population Exposure
I	–
II-III	50,000
IV	7,470,000
V	6,360,000
VI	930,000
VII	600,000
VIII	2,030,000
IX	910,000
X	120,000

Figure 1. Estimated modified Mercalli intensity (MMI) data and contour map for 2010 Haiti earthquake (USGS 2011).

1.3 million people still lived in Internally Displaced Persons (IDP) camps. One year after the earthquake, 810,000 still lived in these camps, many of which offered only minimal services and little protection from natural hazards such as hurricanes, floods, and landslides (see Figure 4). The reduction in the number of people living in IDP camps was a direct consequence of the assessment program, which allowed people to return to the buildings deemed safe.

MAIN CAUSES OF THE OBSERVED DAMAGE

This earthquake caused devastation disproportional to its magnitude. If any form of standard seismic design and construction had been used in Haiti, many lives and much of the economic loss could have been avoided. The main observed factors that exacerbated this tragedy were the following:

- In Haiti, design and construction practices had not considered earthquake forces. In addition, many engineers and contractors had neither formal education nor experience in earthquake-resistant design methodologies.

Figure 2. Damaged Presidential Palace in Port-au-Prince (UNDP Global 2010).

Figure 3. Collapsed United Nations building in Port-au-Prince (UNDP Global 2010).

Figure 4. A Haitian IDP camp.

- Haiti lacked an accepted building or seismic engineering code and a proper quality control system in design and construction. In addition, no formal building review process was in place.
- The past decade has seen rapid growth of low-income neighborhoods due to migration into the city from outlying areas. In these neighborhoods, unsafe housing had been built using substandard construction materials and practices.
- The country, international organizations, emergency responders, and citizens were not prepared for a major earthquake, and the structural response and preparedness were inadequate for any level.

Many of the structures in Haiti are composed of a particular building type that is seismically vulnerable and poses a life-safety hazard. These buildings use a variation of confined masonry construction comprising weak hollow concrete blocks (HCBs) with lightly reinforced and nonductile beams and columns. It is noted that confined masonry buildings can withstand large earthquakes if proper design, detailing, and construction are implemented. The problem observed with the buildings in Haiti was the very poor quality of construction.

DAMAGE ASSESSMENT PROGRAM

DAMAGE ASSESSMENT METHODOLOGY

The evaluation methodology chosen for this program was the *ATC-20* (ATC 1987) rapid assessment, with modifications made to adapt to Haitian construction practices and to

provide information that is more useful to the MTPTC. This methodology, which was first developed in California in the 1980s, has been used successfully for evaluation after many major earthquakes in the United States. The rapid assessment form allowed evaluators to characterize buildings in one of three ways:

- "Inspected" (also known as "green-tagged"), meaning that the building is structurally undamaged and may be occupied full-time.
- "Restricted Entry" (or "yellow-tagged"), meaning that the building should not be occupied for extended periods and that parts of the building might be considered off-limits.
- "Unsafe" (or "red-tagged"), meaning that the building cannot be safely inhabited.

The form was modified to provide evaluators with a checklist of earthquake vulnerability factors per *FEMA 310* (FEMA 1998), which allowed evaluators to list the features of each structure that would make it more prone to earthquake damage.

One important consideration that was stressed to the evaluators is that while the three-color evaluation system provides an understanding of the hazard associated with a building at the time of evaluation, it does not state whether a building must be demolished. Some buildings given "unsafe" ratings are considered repairable, but the nature of the damage has rendered them unsafe to occupy until repairs can be completed. In the same way, the "inspected" rating does not guarantee that a building will not be seriously damaged in the event of future earthquakes. For example, if another major event of equal or greater magnitude were to take place along a section of the Enriquillo-Plantain Garden fault zone closer to the city of Port-au-Prince, in all likelihood, the damage would be much more widespread. In general, the nature of local design and construction in Haiti is such that nearly all buildings can be considered vulnerable to damage from earthquakes.

One feature of the process was the use of PDAs with GPS capability to assist in performing the evaluations. The PDAs were preloaded with the modified *ATC-20* damage assessment form, and evaluators filled out the forms electronically during the course of each assessment. At the end of the day, all information from the more than 150 PDAs was uploaded to a main server. Because some of the street layout of Port-au-Prince is unmapped and many residences have no formal addresses, the GPS coordinates of each structure were used as the primary means of identification. The use of GPS has also proved to be an invaluable tool for developing overall damage maps and a strategic reconstruction plan.

Evaluations were performed systematically, with each division given responsibility for evaluating all the structures within a given zone each day. Zones were determined by MTPTC using aerial maps, which were updated daily to show the status (green, yellow, red) of each evaluated structure. As each zone was completed, new ones were assigned.

As the program evolved, and as additional funding became available through USAID and PADF, the ten teams were expanded to 17. With all 17 teams working at capacity, it was possible to assess more than 3,000 structures daily. The initial target of 100,000 structures evaluated was met on 31 May 2010, and by 15 June 2010, 133,000 buildings had been assessed. By the end of August 2010, more than 250,000 structures had been evaluated. All of the structures (approximately 400,000) in the earthquake-affected area were assessed by March 2011.

TYPICAL BUILDING CHARACTERISTICS

Although the buildings observed displayed a wide variety of sizes and architectural styles, virtually all were constructed using a similar structural system: a cast-in-place concrete gravity frame with unreinforced HCB infill panels. In typical buildings, these infill panels were not designed as structural elements. However, given their stiffness and their connection to the adjacent members, they acted as infill structural walls and altered the response of the buildings.

In such structures, the concrete floor and roof slabs are supported by lightly reinforced concrete columns, sometimes as small as 150 mm on the side. Floor and roof framing consists in some cases of a grid of concrete joists framing between the beams, and voids between the joists are created using HCBs as stay-in-place forms. Exterior wall cladding and interior partition walls universally consisted of HCBs joined with cement mortar. These infill wall panels effectively serve as the seismic-force-resisting system; however, there has typically been no evidence of any system intentionally designed for that purpose. These buildings typically lacked a seismic load path; in other words, they do not appear to have a system by which inertial forces generated in one portion of the structure could be transferred to other parts of the structure and then to the ground. In seismic zones, this load path commonly comprises of diaphragms, collector elements such as chord and drag reinforcing, special vertical reinforcing at shear wall corners, and doweling between the walls and surrounding elements. None of these were present in the vast majority of buildings observed.

Concrete gravity frames display numerous design and construction practices that would be considered defective by international standards, particularly in seismic zones. Figure 5 shows some of the common seismic deficiencies.

Design defects include the following:

- Inadequate column size (cross section dimensions)
- Insufficient amount of longitudinal reinforcement
- Use of smooth reinforcing bars
- Lack of column confinement reinforcing
- Inadequate lap splices and rebar development length
- Presence of captive columns

Construction defects consist of the following:

- Segregation, voids, and rock pockets evident in finished concrete, particularly in columns and at construction joints
- Exposed rebar and poor aggregate shape and grading
- Poorly located construction joints, and paper and other debris left in joints; formwork embedded in finished concrete
- Out-of-plumb columns

In addition, although no comprehensive material testing was conducted, both the masonry and concrete elements for residential construction appeared to have quite low material strength. For example, there was honeycombing in the concrete columns. For commercial buildings, the quality of material appeared to be better.

Typical masonry construction also had numerous defects, including irregular coursing, missing or inadequate vertical mortar joints, inadequate horizontal joints, poor material

Figure 5. Typical Haitian construction practices showing common inadequacies: (a) Column with poor concrete consolidation, (b) beam with embedded formwork and exposed reinforcing, (c) poor workmanship in unreinforced hollow concrete block wall, (d) building with overhanging upper floor.

quality, and extensive use of broken block. These conditions were found in nearly all the buildings surveyed, regardless of age, size, or number of stories. These design and construction practices led to a combination of heavy buildings with little lateral strength and essentially no post-yielding capacity, and were key factors in the vast majority of failures observed.

BUILDING DAMAGE SUMMARY

Table 1 summarizes the number and the median (50th percentile) damage estimate for the 398,829 buildings evaluated. Fifty-three percent is building stock that is undamaged and safe to use. Twenty-six percent has moderate damage and most likely can be repaired. These numbers are significant, because they indicate that approximately 80% of buildings affected by the earthquake can be immediately occupied or repaired with relative ease.

Table 1. Summary data for damage assessment

	Tag				
Category	Green	Yellow	Red	NA*	Overall
No. of buildings	213,083	102,147	79,481	4,118	398,829
Percentage	53%	26%	20%	1%	100%
Median damage estimate	0%–1%	10%–30%	60%–100%	–	–

*"NA" denotes not available. The entries for these buildings (approximately 1% of the total) were not recorded.

The median damage estimate was computed from the histograms of Figure 6. During the assessment process, the damage for each structure (regardless of the assigned tag) was classified in the following subsets: none (0%), 0.1% to 1%, 1% to 10%, 10% to 30%, 30% to 60%, 60% to 99%, and complete (100%). The data was then normalized for each color-tagged building, and the median damage estimate was computed.

The majority of the damaged and collapsed buildings were in the low-lying districts west of the airport, which includes downtown Port-au-Prince, Nazon, Turgeau, Canape-Vert, Carrefour, and the lower portion of Delmas. By contrast, more southerly and easterly regions, in particular Juvenat and Pétion-Ville, suffered much lighter damage (see Figure 7). The difference in damage levels is mainly a result of soft-soil amplification (Seed and Idriss 1982), geographical effect, and construction quality. Softer soil is found in many of the high-damage areas.

DAMAGE CLASSIFICATION

By far, the most common damage found among the buildings evaluated was cracking or collapse of the HCB walls, which is a natural consequence of both the lack of reinforcement and the poor material quality. Among the buildings evaluated, moderate or serious wall cracking was cited in nearly 160,000 cases, or 40% of the total assessment. Wall collapse was noted in approximately 120,000 cases, or 30% of the total. Cracking was observed to

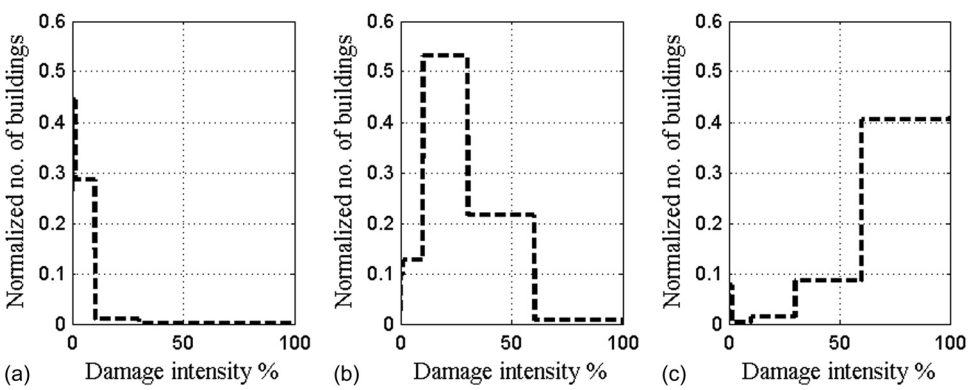


Figure 6. Histograms of damage intensity for all assessed buildings: (a) Green-tagged, (b) yellow-tagged, and (c) red-tagged.

Figure 7. Map of Port-au-Prince showing the location of green-, yellow-, and red-tagged buildings as of March 2011.

be most widespread in the lower levels of multistory buildings, where shear forces were highest. The next most common damage mode was either cracking or crushing failure of concrete columns, in about 91,000 cases, or about 23%. Table 2 summarizes the damage types by number and percentage of total buildings assessed.

In Haiti, two types of confined masonry construction were typical: one with a concrete roof and one with a gable metal roof supported by wood rafters. Both types experienced substantial damage, but the typical mode of failure was different. In general, the units with concrete roofs usually had in-plane shear failure, whereas the structures with sheet metal

Table 2. Comparison of damage types found in the greater Port-au-Prince area

Damage classification	No. of buildings	Percentage*
Exterior, interior wall cracking	159,574	40%
Exterior, interior wall collapse	119,287	30%
Column cracking or spalling	91,391	23%
Slab, beam, joist cracking or spalling	73,899	19%
Parapet, canopy, deck, stair damage	60,204	15%
Ground movement or cracking	52,909	13%

*Note: Percentages were taken as the total number of affected structures divided by the number of surveyed units (398,829). Percentages in this column exceed 100% when added because: (a) many structures had more than one classification of damage, and (b) some of the buildings did not experience the classifications of damage listed in this table.

and wood roofs experienced out-of-plane failures. However, this data was not collected during the assessment process.

DAMAGE BY BUILDING OCCUPANCY

Overall, damage did not vary substantially between building occupancies, but some trends can be seen from the data. The vast majority of evaluated buildings (approximately 290,000 units, or about 75% of the total number of assessed buildings) were single-family residential structures. These structures varied widely in quality of construction, and ranged from large, engineered mansions to improvised shacks. Table 3 presents the distribution of damage for various building occupancies. Examination of the data in this table shows the following:

- Commercial/industrial, healthcare, and civic buildings, which are often larger, engineered structures, had better performance overall, with 64% (for commercial buildings) of these building types being green-tagged, as opposed to 54% for single-family housing.
- The performance of essential facilities, such as hospitals and public-safety facilities was not adequate. In healthcare, for example, the damage rate corresponded to a loss of healthcare capacity of approximately 36% immediately after the earthquake, a time when this capacity was needed most.
- The best overall performance (as measured by the largest percentage of green-tagged buildings) was experienced not by essential facilities (such as police and fire stations), but by commercial/industrial facilities.
- An especially alarming finding was that one of the worst performance levels among occupancy types was experienced by schools, for which more than 50% were tagged as either yellow or red.

Figure 8 presents histograms of the observed damage intensity for various occupancies. (Data is shown only for cases where the sample size in the database was large.) The data used to construct the figures was obtained using the damage assessment database, which

Table 3. Classification (percentage) for various color tags and building occupancy types

		Tag**			
Building Occupancy	No. of buildings*	Green	Yellow	Red	Yellow + red
Single-family residential buildings	290,381	54%	25%	21%	46%
Multifamily residential buildings	70,175	54%	30%	16%	46%
Schools	3,317	49%	30%	21%	51%
Healthcare buildings	857	64%	22%	14%	36%
Civic/public-safety facilities	4,061	56%	26%	18%	44%
Commercial/industrial facilities	15,974	64%	21%	15%	36%
Other	3,935	51%	29%	21%	50%

*The total number of buildings does not equal the number of assessed buildings because some buildings have more than one type of occupancy.
**Only the data for the buildings tagged was used. The data from the approximately 1% of buildings not tagged was not used.

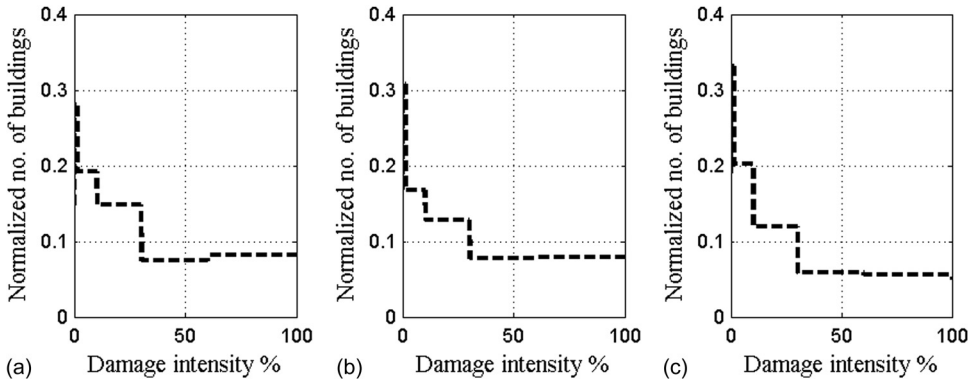


Figure 8. Histograms of damage intensity for various building occupancies: (a) Residential, (b) school, and (c) commercial.

listed the level of damage (from 0% for none to 100% for collapse) and the number of buildings in each occupancy category that experienced a given level of damage. The horizontal axis is the number of surveyed buildings in each category normalized with respect to the total number of buildings surveyed. The median damage for these occupancies is in the 1% to 10% range.

Examination of the data in the figure shows the following:

- For residential and school buildings, greater damage was observed, which led to a higher level of damage for the median surveyed building.
- For single-family homes, the main cause of the higher damage median is the large number of nonengineered buildings.
- School buildings are vulnerable for two reasons, as listed below. These vulnerabilities are common in many other countries as well. For example, the authors witnessed more than 7,000 classrooms that were destroyed in the 2008 Sichuan, China, earthquake (Miyamoto et al. 2008). The primary causes of damage are the following:
  - The presence of many windows introduced captive columns in the structure.
  - Fewer wall elements were used per square meter of the structure. Although this data was not measured during the assessment, such construction is typical.

DAMAGE AS A FUNCTION OF THE NUMBER OF STORIES

In general, the evaluation showed that building performance (as measured by the percentage of red-tagged structures in each group) was progressively worse as building height increased, and tall buildings were much more susceptible to severe damage. Of the buildings that were four stories or more in height, 40% were red-tagged; versus 20% for one-story buildings (see Table 4). In other words, the potential for catastrophic failure or collapse is almost twice as high for buildings of four-stories or more as for one-story buildings. This trend is shown clearly in Figure 9, where at the median number of surveyed buildings the damage level increases significantly as the number of floors increase in a building.

Table 4. Classification (percentage) for various color tags and number of stories

		Tag**			
No. of stories	No. of buildings	Green	Yellow	Red	Yellow + red
One	325,106	54%	26%	20%	46%
Two	63,547	55%	26%	19%	45%
Three	8,776	43%	26%	31%	57%
Four or more	1,365	36%	24%	40%	64%
NA*	35	–	–	–	–

* "NA" denotes not available. The entries for these buildings (approximately 1% of the total) were not recorded.
** Only the data for the buildings tagged was used. The data from the approximately 1% of buildings not tagged was not used.

DAMAGE AS A FUNCTION OF VERTICAL IRREGULARITIES

Vertical irregularities such as setbacks, discontinuous shear walls, soft stories, and coupled shear walls had an adverse effect on building performance. 0 presents the surveyed buildings with vertical irregularities. For reference, data from 0 (which includes all buildings surveyed and is repeated here as the first row of the table) is also included. As the table shows, the introduction of vertical irregularities significantly increased the chance of a building being tagged yellow or red. In particular, it is noted that approximately 50% of all buildings with captive columns were red-tagged. This number is in contrast to the overall 20% red-tagged buildings for the total surveyed population.

Figure 10 presents histograms for the buildings with vertical irregularities. It is noted that the buildings with captive columns have a much larger median of damage intensity compared with the other types of vertical irregularities.

The actual performance of buildings with these irregularities, particularly soft stories and captive columns, was likely worse than shown by the data in Table 5. In many

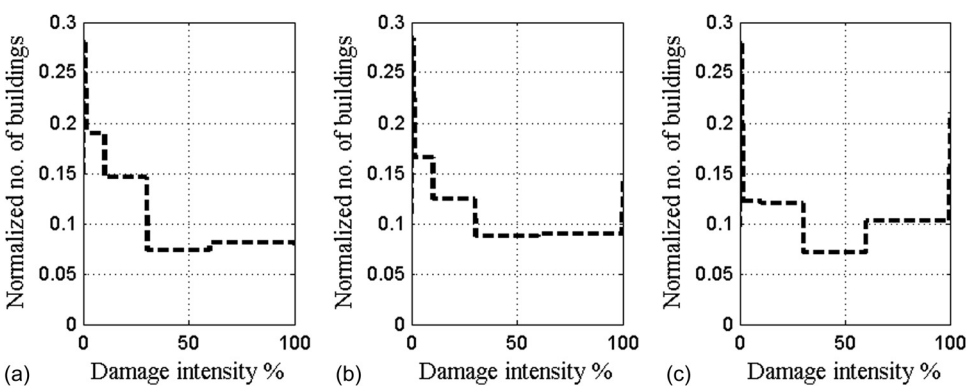


Figure 9. Histograms of damage intensity for various numbers of stories in buildings: (a) One and two stories, (b) three stories, and (c) four or more stories.

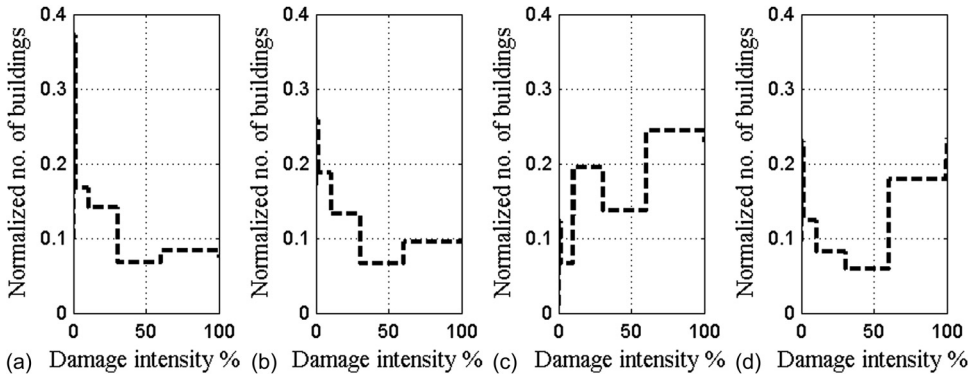


Figure 10. Histograms of damage intensity for buildings with vertical irregularities: (a) Soft story, (b) setback, (c) captive column, and (d) pounding.

instances, soft stories and captive columns led to total collapse, making the underlying irregularity difficult to detect. Therefore, the actual number of red-tagged buildings with a soft story or captive column is larger than the 21% and 49% values, respectively, shown in the table.

STRUCTURE REPAIR AND RECONSTRUCTION STRATEGY

OVERVIEW

By March 2011, approximately 400,000 structures had been assessed, and out of those, approximately, 182,000 structures (about 46%) were identified as damaged by the earthquake. Approximately 80,000 structures (20%) had been red-tagged as unsafe to occupy, and approximately 102,000 structures (26%) had been yellow-tagged as limited entry per the *ATC-20* protocol. Out of the approximately 182,000 structures identified as damaged, 102,000 were identified as feasible for repair, and 80,000 would have to be replaced with transitional shelters (T-shelters) and new structures. Considering that at the time of this writing, more than 810,000 people are living in IDP campsites, meeting the construction needs for these 182,000 structures in a safe and timely manner is critical. This reconstruction

Table 5. Classification (percentage) for various vertical irregularities

			Tag			
	Category	No. of buildings	Green	Yellow	Red	Yellow + red
Vertical Irregularity	Entire pool	398,829*	53%	26%	20%	46%
	Soft story	35,624	55%	24%	21%	45%
	Setback	24,707	55%	22%	23%	45%
	Captive column	22,276	36%	15%	49%	64%
	Pounding	43,625	48%	27%	25%	52%

* The entries for approximately 1% of the total were not recorded.

program, in combination with a red-tagged structure assessment program and a yellow-tagged structure repair program, is an important component to enable all displaced people to move back to their communities safely.

REPAIR ASSESSMENT OF YELLOW-TAGGED STRUCTURES

Overview

A large number of buildings with HCB and masonry construction have experienced HCB cracking damage. Countries such as the United States and Japan have a number of retrofit options for these types of confined masonry and masonry infill wall structures. The American Society for Testing and Materials (ASTM 1993) provides examples of several such approaches. Some examples include placing fiber-reinforced plastics, applying engineered cementitious composite (ECC), adding steel braces, and adding reinforcement to the wall.

Given the need to use readily available local material, considering the capabilities of Haiti's masons, and accounting for the economics involved in the repair of such a large number of structures, many of these options are not feasible for the current program in Haiti. For the vast majority of Haitian structures, therefore, the preferred method is placing horizontal and vertical reinforcement in the HCB walls, and using superior concrete mortar mix and masonry blocks. This is one of the procedures discussed in ASTM (1993). This method was selected as the primary approach for repairing failed HCB, since it provides good earthquake performance, offers economic benefits, and takes advantage of the locally available labor and materials for implementation. To demonstrate its efficacy, sample zones have been selected and are undergoing reconstruction before the effort is extended to wider areas of the country.

Repair and Reconstruction of Damaged and Collapsed Residential Structures

The data assessment shows that approximately 26% of the evaluated structures have been classified as yellow-tagged. These structures must be repaired expediently using safe earthquake engineering techniques to help reduce the number of people living in temporary camps.

Unfortunately, there is ample evidence that pre-earthquake, unsafe methods are being used for the reconstruction and repair of these collapsed or damaged structures. Such an approach would place the lives of the citizens of Haiti at risk again in the event of another large earthquake. Therefore, it is imperative to use an improved and safe repair and reconstruction plan that focuses on techniques, quality control/quality assurance (QC/QA), and an approval mechanism to reduce the future life-safety risk. The proposed plan comprises the following components:

- *Develop cost-effective and simple repair methodologies for typical residential buildings.* The platform uses existing research from leading technical research institutes that focuses on these and similar types of construction, as described previously.
- *Develop guidelines and programs to communicate with and train contractors and communities to repair and reconstruct residential structures.* A simple illustrated guideline and training program was developed based on the previously listed research information listed above. This guideline and training program has been developed for community implementation.

- *Develop a repair assessment method and construction inspection plan.* PDA-based repair assessment and QA have been developed.
- *Develop community-based reconstruction strategic plans using the damage assessment database.* The damage assessment database and the field knowledge developed during the assessment will be used to create a reconstruction strategic plan for each community. This plan will include possible total reconstruction areas, utilities requirements, and the cost of reconstruction and repair.
- *Develop and implement a project communications program for the repair guidelines*. A mass media, strategic public communications campaign will be initiated using the available modes of communication (including radio and community meetings) to inform the public about the reconstruction plan and promote the use of improved repair and reconstruction methods.
- *Project schedule*. The authors have been executing a pilot project with PADF funded by USAID. The first batch of 2,000 yellow-tagged structures was repaired by March 2011. Many thousands more yellow-tagged structures are expected to be repaired in 2011. The majority of the reparable structures would be repaired by the end of 2012.

STRATEGIES FOR RED-TAGGED STRUCTURES

Identification of and Tactics Development for Red-Tagged Structures

At each site, trained Haitian engineers will perform the following tasks, as well as collect and record the data. This data will be used in the community—with the involvement of NGOs—to implement red-tagged structure repair, demolition, and reconstruction efforts, as well as T-shelter construction

Detailed Assessment of Non-Collapsed Structures

The non-collapsed structures will be assessed in detail to confirm their red-tagged status and repairability. If the red-tagged structures are evaluated as feasible for repair, the repair assessment program will be conducted on the structure. If the red-tagged status and condition as infeasible for repair are confirmed, then the following data will be recorded:

- *Classification of demolition*. The demolition will be classified into one of the four groups listed in the following section, and information will be recorded to document the reasoning behind the qualification.
- *Means and method of demolition*. Given the classification of the demolition, on-site recommendations will be recorded on the means of demolition and the type of equipment and personnel that would be required for removal.
- *Quality of site access*. The quality of access to the site will be determined; for example, what type of construction and demolition equipment can be brought to the site, if any, and whether the site allows for debris-hauling equipment. In addition, it will be determined whether the site would allow access for implementing the demolition requirements listed in the next section.
- *Estimation of debris volume*. The volume of debris that would be generated during the demolition will be estimated.

- *Means and methods of debris removal*. Given the volume and type of debris, on-site recommendations will be recorded on the type of debris removal and equipment needed to achieve such a task.
- *Identification of T-shelter and new construction requirements*. Given the size of the site and the number of tenants that the building had, an estimate will be made of the size and number of T-shelters and housing that would be required until a new replacement structure had been erected.
- *Identification of natural and geohazard conditions*. An estimate of flood hazards and geohazards at the site will also be made. This estimate involves documenting any unusual site conditions, including flooding potential; noting any peculiarities about the site that had amplified the response; and noting other hazards such as slope stability and proximity to faulting. This data will then help engineers in the next phase of the reconstruction effort.

Classification of the Demolition

During the damage assessment structure evaluation, the engineers also assessed and documented the means by which the building could be demolished. Four categories have been developed:

- *None or minor*. These buildings collapsed completely, essentially turning into rubble. No demolition or only minor demolition or structural removal is required. Essentially, the only task remaining is the debris removal and cleaning of the site.
- *Simple.* These buildings are typically one story tall. They still have some small parts standing. However, the remaining portions can be dismantled and removed by hand crews using simple hand tools. No engineering technical support is needed because the remaining structure does not present a life-safety hazard to the crew removing it.
- *Average*. These structures are two to three stories tall and experienced partial collapse at some floors. They require engineering expertise to safely remove the remaining portions of the units.
- *Complex*. These groups of buildings are typically tall and experienced collapse of floors at intermediate levels. The buildings are still standing. The removal of these buildings should be undertaken by construction and demolition specialists who have the experience, technical support, and heavy equipment required to remove the buildings safely and incrementally.

Table 6 presents the assessment of demolition difficulty data for red-tagged buildings.

QC/QA STRATEGY FOR YELLOW- AND RED-TAGGED STRUCTURE REPAIR AND RECONSTRUCTION

Ten engineering divisions (150 national engineers) should be deployed as part of the repair assessment program, and another ten engineering divisions have been deployed for a red-tagged structure assessment program to conduct detailed engineering assessments of approximately 182,000 damaged structures for reconstruction within a reasonable time

Table 6. Classification of demolition difficulty for red-tagged buildings

	Demolition classification					
	None/minor	Simple	Medium	Complex	NA*	Total
Number	27,122	24,550	10,105	6,628	11,076	79,481

* "NA" denotes data not available.

frame. The repair assessment program was initiated in Delmas 32 in August 2010, but a total of ten divisions are required for area-wide repair assessment.

The QC program should support yellow- and red-tagged structure assessment and reconstruction programs. The QC/QA program should include:

- *QA of yellow- and red-tagged structure assessment programs*. A construction-quality monitoring platform has been developed and a PDA-based monitoring tool is being implemented for yellow-tagged structure repair and reconstruction. This tool should also be used to provide a construction QA process. A similar tool will be developed for new construction.

These QC/QA program procedures are critical activities for reconstruction. The authors have found that many Haitian engineers are more than capable of being trained in and implementing these yellow- and red-tagged structure programs with a proper QA program. This QC/QA program is also an integral part of the capacity development program in Haiti. Trained and experienced engineers from damage assessment, yellow-tagged structure assessment, and red-tagged structure assessment programs should be brought over to the QC/QA program.

CONCLUSIONS

The 2010 Haiti earthquake once again revealed the vulnerability of unreinforced masonry and nonductile concrete construction to earthquake damage. The problem was more severe in Haiti because the country was unprepared for a major earthquake; no seismic event had occurred there for more than 150 years. To address the special circumstances and damage assessment in Haiti, an international and national partnership was formed, and it has focused on inspection and reconstruction. This effort has shown that:

- An innovative assessment approach that relies on the expertise of international engineers to train national engineers in using state-of-the-art technology—such as *ATC-20* and *FEMA 310* protocols, PDAs, and GPS—is effective for rapid assessment and data collection.
- Such an event provides a unique opportunity to collect field data and to develop fragility functions for various building types, occupancies, and construction.
- Using a rapid assessment program as a database for reconstruction is an effective methodology. The methodology developed in Haiti can also be implemented in other parts of the world as an effective damage assessment and reconstruction method.

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